→ THE EUROPEAN SPACE AGENCY

EXTENDED REALITY & TN/NTN

By ESA CSC (Connectivity and Secure Communications)
Space for 5G/6G and Sustainable Connectivity

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Editors: James Talbot and Antonio Franchi

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LIST OF ACRONYMS

Acronym	Definition
4G	4th Generation
5G	5th Generation
5G MPN	5G Mobile Private Network
6G	6th Generation
AI	Artificial Intelligence
API	Application Programming Interface
AR	Augmented Reality
AV	Autonomous Vehicle
BVLOS	Beyond Visual Line of Sight
CAD	Computer-aided Design
DL	Downlink
eMBB	enhanced Mobile Broadband
FOV	Field of View
FL	Federated Learning
FR1	Frequency Range 1
FR2	Frequency Range 2
GEO	Geostationary Orbit
GSMA	Global System for Mobile Communications Association
HUD	Heads-Up Display
ML	Machine Learning
mMTC	massive Machine to Machine Type Communications
MPN	Mobile Private Networks
MR	Mixed Reality

Acronym	Definition
MRI	Magnetic Resonance Imaging
ML	Machine Learning
mMTC	massive Machine to Machine Type Communications
MR	Mixed Reality
MRI	Magnetic Resonance Imaging
CT	Computer Tomography
NTN	Non-Terrestrial Network
O-RAN	Open Radio Access Network
PDU	Protocol Data Unit
QoE	Quality of Experience
QoS	Quality of Service
R&D	Research & Development
RAN	Radio Access Network
SDK	Software Development Kit
TRL	Technology Readiness Level
TN	Terrestrial Network
UI	User Interface
UL	Uplink
URLCC	Ultra Reliable Low-Latency Communications
V2X	Vehicle-to-Everything
VR	Virtual Reality
XR	Extended Reality

EXECUTIVE SUMMARY

Extended Reality (XR) – which encompasses Virtual, Augmented, and Mixed Reality – is poised to become a transformative force across industries, enabled by the seamless integration of terrestrial (TN) and non-terrestrial (NTN) networks with 5G and future 6G technologies. Just as the Internet and mobile connectivity reshaped society, XR promises to revolutionise how we work, learn, heal, design, and explore.

The European Space Agency (ESA) recognises the strategic importance of XR and its reliance on robust, global, and secure connectivity. Ubiquitous TN/NTN convergence ensures XR applications can thrive everywhere—from remote energy facilities and underground mines to hospitals, classrooms, and even space missions.

This white paper highlights the breadth of XR use cases, and outlines the corresponding TN/NTN requirements and enablers needed to support them:

- **Industry and Automation.**
  XR-powered digital twins, CAD integration, and NVIDIA Omniverse platforms enable real-time collaboration, resource optimisation, and safer workplaces.

- **Energy Sector**.
  XR-assisted maintenance, remote operations, and risk management improve efficiency and sustainability, reducing downtime and costs.

- **Training and Healthcare.**
  Immersive XR environments provide safe, cost-effective training for engineers, doctors, and students, while enabling patient consent, medical education, and remote rehabilitation.

- **Telepresence and Entertainment.**
  XR creates new ways to connect, stream, and interact with people, media, and events, redefining engagement across business, culture, and leisure.

- **Space Exploration.**
  Astronauts and mission control benefit from XR training, remote diagnostics, and telepresence; supporting both operations and crew wellbeing.

As adoption accelerates, open standards, interoperability, and collaboration are critical to ensuring scalability and widespread benefits. Challenges remain—such as device accessibility, cost, latency, and content availability—but advances in 5G/6G NTN and AI-driven networks are closing the gap.

ESA advocates for global partnerships to advance XR readiness, foster innovation, and deliver secure, resilient infrastructures that support Europe's leadership. XR is not a distant vision, but an emerging reality that demands action today.

"Just as the internet and mobile connectivity reshaped society, XR promises to revolutionise how we work, learn, heal, design, and explore"

1. INTRODUCTION

There was a time when students in schools had to ask permission to type their schoolwork in a computer's word processor. It was once equally uncommon for documentation and signatures to be trustworthy in paperless form, and for most life's daily tasks to be carried out on a device that fits in our pockets. Even more surprising, there was a time before the internet, when people were not connected everywhere, all the time. Of course, the above are all part of daily life now, and it is quite difficult for some to image life without computers, smartphones and the digitised world we inhabit. Just as these technologies have changed our world through connectivity, so too will Extended Reality (XR) devices—through TN/NTN seamless connectivity—change the world again.

The European Space Agency advocates continuously for the advancement of new and emerging technologies. The growing use of XR in a variety of use cases enabled by ubiquitous coverage is clear. This white paper aims to outline existing and new industries where satellite communications and 5G/6G TN/NTN integration benefit XR, the outlook for XR with the advent of 6G and ESA's vision to deliver space for XR in the 21st century.

1.1 WHAT IS XR?

XR, is a term for technologies helping to engage and blend the computer's virtual environments and experiences with that of the physical world.

Before diving into the variety of use cases for XR technology enabled by satellite connectivity, it is important to provide an overview of the current terms used often to describe the various mediums.

- **Virtual Reality (VR):** The traditional headset/goggles, controllers we're all familiar with that has begun to evolve into smaller and lighter headpieces, and the choice to operate with or without physical controllers (i.e., hand gestures). This experience is typically the most immersive as it allows the user to be "transported" to another place or time. The user's field of view (FOV) is completely engulfed in the VR headset with no view of the outside world. For a time, Virtual Reality as a term was synonymous with all types of applications related to a headset device.

- **Augmented Reality (AR):** This aspect of XR has refined itself into one of the most versatile forms of the medium. To begin the comparison, AR is like VR in that the users wears a headset

and, in some instances, utilises controllers in the hands, but this is where the similarities diverge. AR headsets allow the user to also see the physical environment around them either using colour passthrough vision (i.e., cameras mounted on the headset to view the outside world) or using lenses akin to clear glasses allowing the AR experience to be "projected" onto and around objects in the real world. This XR medium can also be used with handsets (e.g., tablets, smartphones) that interact with or operate independently from the AR headset. AR Headsets often make exclusive use of hand gestures to navigate experiences thus removing the need for complex controller systems that require the user to adapt to different button layouts and allows them to use their index fingers to explore the AR experience.

- **Mixed Reality (MR):** MR is often used to describe experiences that are in AR, but generally, MR has become somewhat the precursor to the current moniker for Extended Reality applications (XR). MR referring to the blend between real world and virtual reality (i.e., Augmented Reality). It is still acceptable to refer to an AR application as a MR application, of course. It is important to be aware of the distinction when communicating within academia or technical specialist (e.g., Unity Developers, Unreal Engine Developers).

- **Spatial Computing:** This is a relatively new term that refers to utilising a VR/AR headset to interact with a PC, tablet, or smartphone much in the way that a computer monitor allows for today. The term is often used as a "catchall" like XR.

For the duration of this white paper, unless explicitly mentioned, all content pertaining to augmented or mixed reality will be referred to as XR, with VR being referenced separately.

1.2 XR WORKS AT ESA

XR AND 5G/6G, NTN AND AI HUBS

ESA's flagship ECSAT 5G/6G Hub has been a strong advocate of XR technologies since its inception in early 2021. Along with the Hub's advanced connectivity solutions (e.g., LEO, GEO, 5G MPN, mmWave), the Hub features a fleet of XR headsets and custom in-house software designed to educate and inform leaders, standardisation bodies, government officials, industry and academia in the benefits and use cases of 5G/6G TN/NTN systems.

As a fortunate consequence, users are also able to experience the ease with which one can navigate and utilise existing XR headsets and technology. Hub participants explore 5G/6G projects and programmes in MR, travel to lunar bases, and interact with future 6G satellite platforms through a range of software designed for simplicity and a clearly defined message that 5G/6G NTN will change the way everyone and everything connects. These demonstrations have been shared at many worldwide conferences (including Mobile World Congress in Barcelona) and for leaders around the world. To date, the ECSAT 5G/6G Hub has hosted thousands of visitors from industry and continues to form lasting collaborations and expansions to support European industry.

The Hub also works with industry and academia developing new solutions for connectivity and XR hardware/software in the realm of satellite communications through ESA's Advanced Research in Telecommunications Systems

programme (ARTES) designed to support industry development to keep European and Canadian industries at the forefront of technology development.

With the advent of ESA's AI Hub in 2026, and the development towards converged networks in 6G, XR will continue to be a staple application for demonstrations, engineering, development and remote operation support to industry and academia. With this new Hub focus on AI for NTN, optimisation works will strive to improve XR use cases over future networks where stability and throughput are key.

To work with the ECSAT 5G/6G Hub, and the AI Hub, towards a potential project or collaboration, please don't hesitate to contact 5G@esa.int or AI@esa.int for AI Hub related activities.

To learn more about ESA's ARTES programme and how it might be able to support your XR solution with TN/NTN, please reach out to 5G@esa.int for details.

XR LAB AND ESA SPACESHIP

The XR Lab at ESA's European Astronaut Centre (EAC) is a research and innovation facility focused on applying virtual, augmented, and mixed reality technologies to astronaut training, mission preparation, and public engagement. This dedicated XR Lab at ESA's emerged in the late 2010s as part of a broader push to make immersive technologies more relevant in human spaceflight. Its work includes developing virtual reality training environments for astronauts, simulating lunar and orbital habitats, and supporting mission design.

ESA Spaceships is a network of innovation teams dedicated to enabling exploration activities together with ESAs partners and agencies. Spaceships support and initiate low-TRL R&D activities—like XR for space exploration, astronaut health, digital twins and more.

ESA continuously strives to evolve capabilities in future technologies and all aspects of the XR ecosystem. Throughout this white paper, the benefits of TN/NTN will be discussed alongside industry partners working to bring XR solutions connected by satellite to fruition.

1.3 5G AND 6G CONNECTIVITY

5G is the fifth-generation technology standard for mobile networks. The integration of satellites into 5G interconnects the terrestrial cellular networks of phones and signal towers with satellites orbiting the Earth and eventually, the Moon. 5G is designed to provide robust and ubiquitous communication connecting people, objects and devices.

6G is the sixth-generation technology standard for mobile networks. The integration of satellites with 6G is increasingly important, not only to leverage the successes of 5G integration, but also to increase the contribution that satellites play in the ever-evolving global connectivity requirements. With 6G, the end user can be anything from a person with a device to an autonomous drone, a robot, a heart monitor, an AI security application, and more. 6G will add connective intelligence and offer unrivalled performance characteristics using native-AI with networking, with integrated sensing, learning, and processing capabilities. AI will bolster the capabilities of the network through AI RAN, continuously optimising and reconfiguring it for peak performance. The 6G Industry Association has declared 6G to feature native-AI features, where intelligent systems are inherent to the function of future network designs. Communications networks will serve as sensors, enabling a better understanding of the physical world and providing a broad range of services.

Moreover, 6G will enhance the existing 5G attributes and fully integrate them with the 6G standard.

1.4 WHY 5G AND 6G NTN?

5G NTN and future 6G NTN technology will support the connectivity demands of XR. The economic impact of 5G and 6G is expected to result in an annual global benefit worth up to $13.2 trillion by 2035[1]. New NTN connectivity networks are being designed with this future in mind; Satellites are critical aspects of these networks, guaranteeing connectivity in a ubiquitous, secure, and resilient way. Integrated, converged TN/NTN networks provide the connective fabric to support the digitalisation of industry and society. ESA realises the need for TN/NTN convergence and global standards to enable all TN/NTN use cases, including those of XR.

Some of the core features promised by 5G and their associated challenges are:

- **Bandwidth:** 5G throughput in countries like South Korea reach speeds of 767 Mbps and in the US, 404 Mbps each individual user. This is likely to result in an unprecedented bandwidth requirement imposed on 5G networks, both terrestrial and their satellite assistants in orbit. To mitigate these challenges, careful network planning will be required to satisfy different users and use cases over the same 5G network.[2]
- **Massive Numbers of Connected Devices:** 5G is designed to accommodate a myriad of connected devices forming the Internet of Things (IoT). This can be anything from a smart phone to a temperature sensor in an office building. Our world is comprised of IoT devices, and with each passing day, we will only see more of these devices at home and in the workplace.
- **Mobility:** As different users and use cases rely on connectivity everywhere, 5G will have to accommodate a wide range of mobility use cases and provide the security and continuity required to support them. Whether the user is on land, sea or air, the 5G network must follow; the same is true for planes, trains and ships.
- **Broadcast:** Many use cases will necessitate broadcasting the same information to a variety of geographically dispersed users at the same time. Optimising content delivery for these cases is important to minimise any network strain. Satellites can deliver rich multimedia content across multiple sites simultaneously and efficiently, using broadcast/multicast streams with an information-centric network and content caching for local distribution.
- **Security:** With end-to-end security being one of the promises of 5G, it's no surprise that widespread adoption has been accelerated across the globe. Preventing improper access to user data—no matter the content—is a foundation of 5G protocols and instrumental in substantiating the data security promised by 5G.
- **Reactiveness (Low Latency):** Some of the 5G use cases (such as haptic and tactile internet-enabled telesurgery) demand very high reactiveness and low latency connectivity. The 5G network will need to implement mechanisms to minimise network delay and distribute information towards the edge of the network to optimise response time.
- **Ubiquity:** Public demand dictates that 5G be available in rural and remote areas as well as in city centres. This is challenging, given the relatively low coverage range of individual 5G base stations and the slow deployments of terrestrial 5G networks, which inevitably prioritise city centres. For the promise of ubiquity to be realised, satellite telecommunication networks will be needed to complement 5G terrestrial coverage, providing high-speed capacity across the globe. 5G networks must operate seamlessly across a set of heterogeneous network elements, with satellites playing a critical role. Network convergence is the key to a future in which new players emerge (such as virtual network operators), pooling terrestrial and satellite services in different domains and use cases. Innovation and novel service developments will benefit from this integration of satellite and terrestrial service required by each service domain.

The two primary applications with significant potential for NTN are eMBB and mMTC, driven by the broad coverage area offered by satellites.[3] This capability allows satellite systems to provide connectivity to underserved or unserved regions, such as islands, ships, aircraft, and remote areas, where terrestrial communication infrastructure is either limited or unfeasible. Satellites are essential for ensuring global connectivity, particularly in regions with inadequate terrestrial networks. The integration of AI further enhances their performance by:

- **Beamforming optimisation:** AI adjusts satellite beams dynamically to maximise coverage, enhance signal quality and minimise interference, addressing challenges posed by diverse geographies.
- **Mobility management:** AI ensures seamless and uninterrupted connectivity by intelligently managing handovers between terrestrial and satellite networks.
- **Energy efficiency:** AI-driven optimisation minimises power consumption in satellite operations, contributing to long-term sustainability and significantly reduced operational costs.
- **Advanced traffic analysis:** AI-enabled traffic prioritisation ensures critical applications receive the necessary bandwidth, improving user experience across remote and urban settings.

2. XR INDUSTRIAL AND CONSUMER USE CASES

2.1 XR FOR AUTOMATION

Imagine being able to model a fully digital copy of a factory. Every piece of equipment, each sensor, the power requirements, connectivity, output…everything. Now with APIs for nearly all sensors and equipment software easily integrated into platforms offered by Unity, a software development application, industry can interface and interact with a Digital Twin of their facilities around the world, or across the street. These facilities can then be viewed through XR displays to create 3D representations shrunk—or enlarged—to fit in the palm of a hand. The 3D model can be populated with nearly limitless datasets all transmitted to the user anywhere and actively monitored though seamless, global NTN connectivity. Digitalisation of industry in this way allows for better management of resources, troubleshooting, cost-effective repairs, and might offer safer work environments for employees.

2.2 XR FOR INDUSTRIAL METAVERSE

For purposes of this white paper, we will address the Automated Industrial Metaverse, and VTT's Human Driven Industrial Metaverse model.[4] The Industrial Metaverse has been taking shape over the last several years, especially in the post-Covid landscape where remote working and operation became a bedrock for industry operations. ESA sees the integration of 5G TN and NTN networks to be a pivotal step towards adoption and evolution of metaverse scenarios where connectivity APIs work together with digital twins and hardware (e.g., robotic platforms, manufacturing equipment) to realise remote operation and support to industry.

2.3 XR FOR NVIDIA OMNIVERSE

NVIDIA, arguably the world's leading GPU manufacturer and leader, created an ecosystem of APIs and service together into a software development kit (SDK) utilising generative AI-tools to assist developers in creating complex digital recreations of existing equipment, buildings, vehicles, living bodies, and nearly anything that can be simulated in the digital world[5] The Omniverse platform is designed to take advantage of the global $46 trillion manufacturing industry and its desire to digitalise and automate processes.

The Omniverse has already experience success with companies like Microsoft, where their cloud hosting services through Microsoft Azure enable data interoperability for companies like Hexagon working with visualising and designing of digital twins for industry.

Utilising NVIDIA Omniverse Cloud APIs on Microsoft Azure, enable data interoperability and collaboration through advanced visualisation for designing and managing industrial digital twins.

Industrial digital twins will help simulate new processes and streamline development or operation of equipment in place or being developed for installation; even down to delivery of assets that are assembled in a different location.

BMW Group has been utilising NVIDIA Omniverse to develop virtual factories, optimising planning and collaboration to improve productivity throughout entire manufacturing processes.[6] This approach allows factory planners to work in virtual environments powered by NVIDIA Omniverse years before production begins. This digital twin approach enables BMW to plan and optimise its production process in stunning detail, including simulating the physical properties and interactions within assembly lines.

By leveraging NVIDIA Omniverse and advanced network technologies, BMW is revolutionising the design of highly complex manufacturing systems, allowing for real-time collaboration without compatibility limits.

The integration of 5G and NTN technologies enhances this process by enabling real-time, collaborative 3D simulation and digital twin development across geographically dispersed teams. The ultra-low latency and global reach provided by these networks allow creators, engineers, and designers to work simultaneously on complex, photorealistic virtual environments without being limited by physical location or network lag.

2.4 XR FOR THE ENERGY SECTOR

The drive towards making energy production and management sustainable and safe has been a priority for many ESA Member States in the last few years; especially with the ongoing global energy crisis and drive to renewable systems. The XR Industry has acknowledged this step and are already seeing success in the way of operation and maintenance, risk management and optimisation for the sector. Together with the integration of NTN into these terrestrial infrastructures, the energy sector will increase inclusion of new technologies for productivity like XR and AR.

Using AR glasses, technicians can be guided through repair processes of machinery by remote assistance or experts that cannot easily travel to the local problem. They can also use 5G-enabled streaming devices and cameras to augment the XR technology and provide telematics of other systems being modified by changes or adjustments in real time, helping to make repairs or training more efficient.

Subsurface sectors (e.g., mining, oil and gas storage) are currently taking advantage of remote operation and 5G cameras to train and develop specialists on completing tasks remotely where before, days of travel would have to be factored in along with managing an expert that has to be “in two places at once” to support a repair or training. XR is also helping manage legacy systems that require observation to manage instead of integration with digital software systems. Through Augmented Reality, sensors, error messages, or any diagnostic can be monitored remotely via console, and then checked against a technician from afar tapping into a 360-degree 5G camera.

The Nokia real-time extended reality multimedia (RXRM) 8K 5G-enabled camera, co-developed with ESA in the 5G/6G Hub, is an example of such technology, and is already heavily implemented in the above referenced use cases.[7]

2.5 XR FOR TELEPRESENCE

With the advent of video calls and the aftermath of the Covid-19 pandemic, the use of telepresence has become a mainstay in business and casual use. XR is already being utilised to bring people closer together through VR chat rooms, 360-degree videos and content, along with Apple Vision Pro providing Spatial Videos filmed with iPhone to bring memories to life. The use of XR in the realm of telepresence is part of the allure of the technology; to be able to transport oneself anywhere or anytime and experience the sights and sounds of other cities (and eventually worlds) is an incredible power of the technology. Other XR industries are beginning to adapt technologies to open standards that allow for seamless integration of XR content across devices and ecosystems to help advocate for the proliferation of headsets and XR equipment. With Satellite enable systems, users will be able to connect from anywhere on the globe—or the Moon—to experience history, current events, or travel beyond the stars for inspiration, relaxation or education.

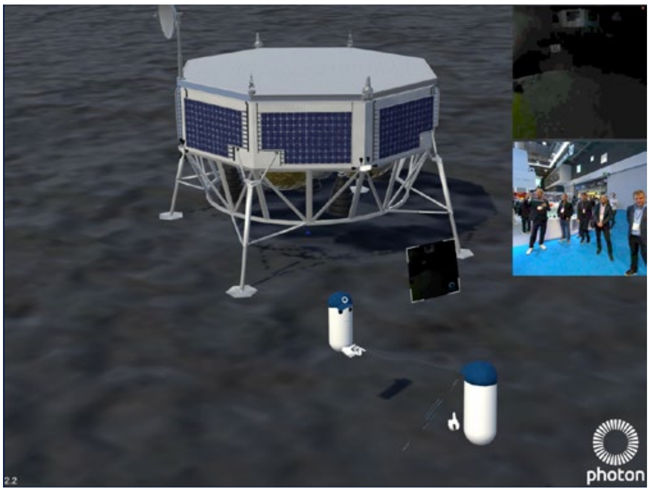
German XR company Photon Engine develop network transport layers to support XR over LEO NTN and have successfully demonstrated its use at Mobile World Congress together with ESA. Their solution is designed for flexibility across system architectures and can stream video, audio and cooperation with digital twins for remote consultation and engineering scenarios.

2.6 XR FOR TRAINING

NVIDIA and other industry partners like Siemens and Capgemini are already leveraging XR technologies to train engineers and key personnel on digital constructs of physical equipment. Using immersive technologies to place individuals in scenarios where complex machinery can be tried and tested along with the skills of the worker presents a cost-effective and safe method of training and developing employees. Safety and operational efficiency are also improved through use of XR by allowing for familiarity of digitalised versions[8] of equipment, software, hardware, etc., thus minimising risk to the company for training, and empowering the employees to learn without fear of damaging multi-million-dollar equipment.

An ancillary effect of XR training is that the digital twin models can then be informed by the choices and decisions made by the personnel using them in the simulations. The training designers can see if the consoles and interfaces work as intended, and the processes on complex new machinery can be trialled and tested before performing critical operations.

XR already enables virtual site inspections for the energy sector (e.g., subsurface mining, ocean rigs, ports of harbour) and assists with remote repairs when the experts are continents away.



Mixed reality application developed with Photon Industries in collaboration with ESA. The application showcases multiplayer environment with streaming audio and video content over LEO satellite.

2.7 XR FOR HEALTHCARE

NHS England believes that XR will be a foundation for the future of healthcare away from hospitals and where patients improve the most: their homes. Health organisations like the NHSX (now being merged with NHS Digital), the National Health Medtech Cooperative (MindTech), Sheffield Hallam University, and UK Research and Innovation (UKRI) are actively supporting a strategy for XR in healthcare within the UK, which will naturally extend to Europe as a whole.[9]

The XR healthcare market is estimated to generate $10 billion in revenues in 2024. Leveraging the successful uptake of XR headsets in the home (up 350% since 2021) because of the COVID-19 pandemic, the NHS and others see the massive market potential for XR in healthcare applications. The NHS South London are already working through their new VR Centre started in November 2024[10] with help from a 30-million-pound investment in NHS organisations to provide "cutting-edge" research to improve disease treatment and management.

Topics cover pain management, patient consent, training for doctors, rehabilitation for stroke victims, amputees, and others. One of the main hurdles to overcome to realise the ultimate in-home patient goal is ubiquitous connectivity. 5G and TN/NTN integration will provide the capability for headsets to connect seamlessly to 5G NTN and stream doctor's instructions or content remotely; be it from the hospital to the home, or hospital to an offshore rig.

Patient consent is often overlooked in technology, but XR allows for perhaps the most robust form of consent available. With an XR device (e.g. a volumetric display, a headset, or even a recording from a headset) patients can view and interact with their CT or MRI scans with a doctor to understand and see what a surgery will entail, what the outcomes might be, and to more than ever before, understand what the doctor will be doing to help them or their loved ones.

XR Helps empower the patient to work with rehabilitation facilities and specialists from all around the world, from anywhere thanks to satellite-enabled connectivity. The use of satellite connectivity for healthcare in the UK has already been in place thanks to companies like Excelerate in Wales and their fleet of 5G and Eutelsat One Web LEO connected emergency response vehicles. With the added capabilities of connected XR devices in the field, ambulances and emergency response teams could have access to floorplans of buildings, streaming of the disaster to expert remote teams, and of course, access to real-time 3D medical scans of patient data.

Through various initiatives to develop connected hospitals through 5G Mobile Private Networks (MPNs), the infrastructure to support XR-based therapies will be in place and easily accessible. One of the major challenges in onboarding the use of beneficial XR technology lies in the connectivity of hospitals to the patient data—and conversely—connecting the patients to the hospital in safe and secure ways; Satellite-enabled communication can provide this link to the local 5G MPNs in

hospitals where necessary for remote areas, and bolster existing infrastructure to support XR technologies advocated for by health developers and organisations worldwide.

Training extends beyond hard surfaces and machinery into the human body for medical education. Students are already studying MRI and CTI scans of organs overlayed onto patients and using these models to inform consent before surgery. Surgeons can also act as over-the-shoulder instructors with XR headsets to observe or consult on a variety of surgical theatres; this was already conducted in the UK NHS with a spinal surgery for a 75-year-old patient in 2024. Mohamed Abdelsadg, a Consultant Neurosurgeon and Complex Spine Surgeon at the NHS Greater Glasgow and Clyde successfully lead the first XR spinal surgery in the UK.[11] The partner company, Brainlab (who integrated X-rays of the patient to create an effective visualisation of the patient's spine), will continue to further integrate the solution and serve as leaders in pioneering the use of XR for surgeries.

There's no doubt that the use of XR will provide a strong foundation on which to train not only humans, but the AI models that support the digital twins, too. These models will improve efficiency and safety in future trainings and provide a basis on which to develop future applications for employees, doctors, students, or anyone looking to learn in a safe, but realistic way.

2.8 XR FOR ENTERTAINMENT

Streaming in all its forms has become one of the primary ways that viewers interact with and view all types of media—from video games to movies, television shows, newspapers and news outlets, the ability to match viewers with nearly infinite amounts of content from anywhere at any time is a business model that will live on for decades to come.

XR is on the cusp of redefining how audiences engage with these types of entertainment, offering fully immersive, interactive experiences that go far beyond traditional screens. As XR headsets and devices become more mainstream, lightweight and powerful, streaming technologies will shift from static 2D content to immersive 3D environments—delivering sports, movies, and in-vehicle entertainment in ways that feel personal, spatial, and real.

In sports entertainment, XR streaming will move fans from the sidelines to the centre of the action. Imagine watching a football match in real-time from the midfield, with the freedom to shift your viewpoint as plays unfold—courtesy of volumetric video captured from multiple angles and streamed in low latency (from technology offered by NOKIA's RXRM camera and that of Apple currently developing 180-degree motion picture cameras.) Interactive stats, player profiles, and dynamic replays could be layered into your field of view, creating a deeply enriched experience. Broadcasters and sports leagues are already experimenting with XR to increase fan engagement and create new revenue streams with personalised viewing subscriptions for each event.

In the film industry, XR streaming is paving the way for spatial cinema where, rather than the audience being passive observers, viewers can be transported into the film's universe, exploring scenes and narratives as if they're part of the adventure. Entire story arcs could be experienced from multiple perspectives, offering greater narrative complexity and audience interactions. With real-time rendering and cloud-based delivery over 5G and NTN, streaming providers can offer adaptive, high-resolution environments that adjust based on the device (e.g. an XR headset, or a smart phone), or its bandwidth (NTN or 5G). This form of moviegoing experience unlocks new creative possibilities for film directors, while expanding content accessibility across both traditional and emerging platforms.

2.9 XR FOR INFOTAINMENT

Streaming content to vehicles is another foreseen benefit of XR technology. Infotainment, or the content that contains entertainment (e.g., films, movies, games) and telematic information (e.g., speed, distance, vehicle health) being streamed to a device readily accessible by drivers and passengers, is a market where XR can provide significant advancements. Through APIs, software companies can allow access to sensors and other hardware within a vehicle or on the road to update drivers in real time with information[12] relevant to the vehicle they are driving or the conditions of the road outside. BMW is already experimenting with XR technology for Heads-Up Displays (HUDs) in vehicles for drivers to get directions and signals overlayed upon real world elements, and to receive updates throughout a given route.

The success of these experiences relies heavily on real-time data delivery, which is where the combination of low-latency XR streaming and modern network infrastructure becomes critical. With the support of LEO satellites and 5G NTN, high-bandwidth, immersive content can be delivered to users wherever they are—whether in a stadium, a rural cinema, or a moving vehicle crossing a remote mountain pass. The global coverage of LEO constellations ensures consistent service quality, while edge processing onboard the vehicles minimise lag for real-time interactivity.

2.10 XR AND AI

As mentioned in ESA's earlier AI for NTN white paper, the widespread adoption and use of AI for network management—and it's benefit for 6G NTN—hasn't been lost on the use of XR technology[13]. The AI advancements seen today will no doubt improve and assist all the use cases defined throughout this document in many ways that are yet to be identified. AI will enable optimisation of streaming content across the entire software stack and touch all aspects of the user experience. Software will be in a continuous state of evolution while adapting to the needs of end users throughout all XR use cases. This will be a natural extension of the future 6G networks that will fully realise the AI for RAN architecture and disseminate throughout industry as the XR hardware and software adapt to the needs of users and is informed by federated reinforcement learning (Q-learning and deep reinforcement learning).

2.11 XR AND MMWAVE

ESA, together with its Polish industrial partners Microamp and Creotech Technologies, has developed a White Rabbit-based 5G mmWave network (WR5G) with satellite backhaul capabilities, currently being deployed within the ECSAT 5G/6G and AI Hub.

This platform can achieve data transfer rates of up to 10 Gbps in mmWave configurations (non-NTN backhaul), offering a significant advantage for XR streaming applications and connected headsets. Leveraging both FR1 and FR2 spectrum bands for XR testing and development will further contribute to the maturation of both software and hardware solutions.

In the context of future TN/NTN convergence, optimising latency across these hybrid network architectures will be critical. This effort will help guide the development of advanced applications and services, ultimately enabling improved performance and user experience. Such experiments have already been conducted utilising mmWave for XR and streaming during ESA's participation to Mobile World Congress Barcelona 2026, where ESA partners connected to the Luna Facility in Cologne, Germany, to conduct simulated, remote cooperative engineering with XR and camera streaming over mmWave and LEO NTN.

2.12 XR FOR THE FUTURE

Industry is already developing volumetric holograms and volumetric technology that can be displayed at a small scale; many devices already exist albeit at an extremely prohibitive price point. Volumetric interfaces and technology are at approximately the same period of evolution that VR was in the eighties and nineties. Soon, the 5G and 6G networks of the future will be capable of handling the immense data rate and latency demanded of volumetric streams, and along with this, the display equipment, too, with evolve.

Hybrid Holograms[15] are already being created in XR with headsets utilising passthrough cameras to achieve a layer of digital information or environment on top of existing locations, places and things. This technology is with us today, but streaming the content across distances requires a lot of processing power and a high data rate teamed with an advanced network. 5G and future 6G NTN networks will be able to support these ecosystems no matter their location on Earth.

Along with innovating content, the devices and equipment that display XR content will be changing a lot in the coming years. Companies like Meta are already researching sunglass-style AR/XR devices that are low power, lightweight and controlled via voice and eye and hand tracking, untethered to a heavy secondary device; Moore's Law is most certainly at play in the XR device world where multiple headsets, glasses, UIs and other ways of interacting with XR content are always coming to market. Soon enough, as ubiquitous as smartphones and infotainment systems in cars, XR user devices will flood the market to take advantage of the high data rates of 5G/6G networks.

2.13 XR FOR SPACE EXPLORATION

Through ESA's work with astronauts at the European Astronaut Centre in Germany, XR is already being used to teleport astronauts in training to the Moon, Mars, space stations and back again to Earth. The long-term mental health benefits of being able to visit loved ones and locations while in space (or even accessing therapies) is a powerful tool that will support future space exploration in the coming years. XR is already positioned to support the crews and families of explorers to come.

XR capabilities will enable technicians and specialists on Earth to assist with upgrades or repairs to space systems in orbit or on other planets remotely thought low-latency connectivity that will speed up and improve operations in space travel. Medical appointments for astronauts will become easier to manage where doctors can hop on a call to the International Space Station or other spacecraft to discuss symptoms or conduct health and wellness checks for astronauts.

2.14 XR FOR DRONES (UAVS)

XR headsets have been used to stream video from drones in flight for control or observation for a few years now. Drones are now being developed and deployed to connect to 5G MPNs to test mmWave data and video streaming, security operations, and to monitor air traffic control from the skies. With satellites, drones are being used for inspections in areas that lack terrestrial connectivity (e.g., the ocean, offshore oil rigs) to stream and provide important sensor data to operation centres on land, or even experts located on the other side of the Earth. Use cases like these will only continue to develop for use in maritime—both casual and industrial—and commercial aviation.

2.15 XR FOR ROBOTICS

The Robotics industry is already working with XR technology for remote operation of robot platforms and will only see benefits with NTN and 5G integration going forward. Operation centres are beginning to research adding workstations and suites that allow for human control of a robotic platform (i.e., controlling the arms, head position, interacting with objects) with haptic feedback and response from the robot being fed back to the operator. This technology is empowered by 5G NTN to allow robots and their operators to be anywhere in the world. Being able to control or receive telemetry from a robot operating underground, in the ocean, or even in space, will greatly increase the market share for robotics supported by NTN connectivity.

UK-based companies like Auto Discovery and the Oxford Robotics Institute are continuously working to train and develop robotic platforms for use in industry, agriculture, energy and security sectors where XR-enabled control of platforms provides safer situations for employees and operators, and training for challenging or demanding tasks (e.g., high/low temperature environments, high voltage areas, etc.) where remote operation is a benefit.

3. STANDARDISATION

3.1 3GPP FOR XR

The 3GPP Release 18 of 5G standards introduces XR-specific RAN and media features with rendering and latency requirements for XR and metaverse applications in 3GPP. [16] Release 19 focuses on mobility for XR and includes—as a key feature—NTN teamed with machine learning and AI for energy efficiency.[17] Following on in Release 20, features QoS and QoE improvements based on AI and network management will drive XR content streaming towards the future 6G architectures.

There still exist some latency and PDU factors to be managed within 5G networks to accurately handle QoS and QoE for the users, but with AI and ML advancements underway and 3GPP standards evolving, network architectures are converging towards a management plan for the low latency requirements of XR (~10-15ms) to ensure a robust experience for users.[17]

Data transfer rates are already within tolerance for XR streaming content over NTN—when viewed in the scope of 3GPP requirements—with Starlink LEO constellations averaging 200Mbps and Eutelsat One Web around 195 Mbps and have already been shown in ESA demonstrations and ARTES developments underway.

3.2 APIs FOR XR

Software Development Kits like Unity and Unreal Engine can create all the environments and experiences that one might seek from an XR experience. Software engineers have access to a variety of APIs that seamlessly integrate IoT, IIoT, AI LLMs, or a myriad of other features that can be added to an XR training or support experience. These APIs—and their open availability—are key to the advancement of TN/NTN integration with future networks. The work within the GSMA to develop open APIs for NTN have proved a benefit to the space and XR sector by highlighting the importance of ecosystems that are available to developers all around the world. This allows for interaction and debugging (e.g., through GitHub repositories, alpha/beta testing) in a community where users and full stack developers can discuss and improve not only their given software, but also the features of APIs available. One of the key elements of the future for XR and its adoption lies with the magic of APIs.

4. CONCLUSIONS AND CALL TO ACTION

The European Space Agency firmly believes in open standards, and collaboration across ecosystems to ensure the best readiness for integration and adoption of new technologies for space-supported communications. ESA participates to, and is a member of, many standardisation bodies (e.g., 3GPP, GSMA, ITU, GSOA, etc.) working to deliver technical specifications and guidelines for industry to incorporate into terrestrial and non-terrestrial networks. The Agency's fifty-year legacy of advocating in such a manner typifies the global importance and acceptance of open and secure standards.

ESA considers it essential to advance research and experimentation on XR technologies, in particular across varying bitrates, latency conditions and other streaming parameters, to fully prepare the value chain for XR content over satcom and satcom-supported networks. Initial work is already underway in several ESA projects, but this effort needs to be further expanded as demand for XR applications continues to grow across the industries discussed in this document.

Adoption of the technology is already underway; the motion sickness of VR is slowly being replaced by the excitement and use cases of AR. Additionally, medics, teachers and students already see the benefits of being able to project and overlay information onto something physical to add detail or clarification to a project or inform an anxious patient.

Current challenges like price point, general experience with the technology, and availability of content is already beginning to improve. Headsets are also slowly starting to move towards a singularity of form factors and design to help standardise performance and capabilities across devices. These actions should continue, and through collaboration and discussions, be improved upon and assist through broader use by users of all types and fields.

XR will only be improved further by the global adoption of 5G/6G and the integration of terrestrial and non-terrestrial networks. XR has already begun to demonstrate its potential to redefine how industry, education, healthcare and energy sectors operate daily. To truly realise a world of connected people through XR, we must collaborate across borders, industry leaders, researchers, and standardisation bodies. As adoption accelerates in the coming years, we must continue working towards open standards and investing in industry and academia that strive to elevate XR capabilities in the market.

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ANNEX 1: TN/NTN FOR XR TECHNICAL REQUIREMENTS

This Annex outlines the performance requirements for XR applications, and how they relate to 5G/6G TN/NTN.

1.1 KPI GENERAL FUNCTION OVER TN/NTN

The following lists shows the main parameters affecting XR applications over TN/NTN networks and typical range of operating values.

Latency: Latency measures the time from a user's action or head movement to the corresponding visual update on their display, a critical factor for user comfort and realism. Examples of applications and range of latencies are:

Interactive AR/VR to be optimised within 10–20 ms , with high-end systems aiming for ≤10–12 ms.

Telepresence, Training, and Media below 50 ms for real-time collaboration, 100 ms top threshold.

Network Budgets: For cloud- or edge-rendered XR, one-way latency should be 3–7 ms over TN. For LEO NTN, 20–40 ms, GEO/MEO for buffered or asynchronous applications due to their higher delay (e.g, caching).

Jitter: up to 5 ms for conversational or media streaming use and 1ms for collaborative real-time.

Downlink Throughput: 50–200 Mbps per user for compressed XR streaming, rising to 300–500 Mbps.

Uplink Throughput: 10–50 Mbps to support sensor data, SLAM point clouds, video, and telemetry for digital twins.

Reliability: Packet loss below 10^{-3} for interactive sessions and below 10^{-5} for control applications.

Time/Phase Synchronisation: Sub-millisecond synchronisation using Precision Time Protocol (PTP) and <100 microsecond accuracy in factory networks using Time-Sensitive Networking (TSN).

Positioning: Accuracy better than 10 cm indoors and within 1 m outdoors for alignment, drones, and robotics.

Mobility: Seamless service continuity even at high speeds (100+ km/h), essential for vehicular XR and drone operations.

Security and Privacy: End-to-end encryption anchored in hardware root-of-trust, fast authentication, and auditable logging — especially critical for regulated industries like healthcare and manufacturing.

1.2 APPLICATION-TO-NETWORK MAPPING

The table on the following page provides a structured mapping between representative XR use cases and their associated key performance indicators (KPIs). For each selected XR use case, the primary KPIs are identified in the second column, capturing the most stringent performance requirements in terms of latency, throughput, reliability, and synchronisation. The third column outlines the relevant 5G/6G terrestrial network (TN) capabilities and enabling features, including, but not limited to, network slicing, edge computing, QoS differentiation, and advanced radio interface enhancements. The fourth column details the complementary role of non-terrestrial networks (NTN), highlighting their contribution to extended coverage, service continuity, multicast/broadcast support, and resilience in scenarios where terrestrial infrastructure is limited or unavailable.

XR Domain	Primary KPIs	TN Features	NTN Role
Industrial Metaverse / Automation / Robotics	• MTP ≤10–20 ms; • jitter <1 ms; • reliability ≥99.999%; • UL 10–50 Mbps; • positioning <10 cm	• Ultra-Reliable Low-Latency Communication (URLLC); • TSN over 5G; • MEC with GPU acceleration; • deterministic scheduling; • network slicing; • Reduced Capability (RedCap) devices; • precise positioning via RTK/5G	• LEO for resilient back-up and remote sites; • multicast twin updates; • predictive caching; • MEO/GEO for non-interactive sync
NVIDIA Omniverse / CAD	• Downlink 100–400 Mbps burst; • low jitter	• mmWave FR2; • MEC-based render streaming; • QUIC/RTP with Forward Error Correction (FEC)	• LEO for remote collaboration; • multicast for large model updates
Energy Sector (Field XR)	• Coverage priority; • DL 20–100 Mbps; UL 10–20 Mbps; <1 m positioning	• Sub-6 GHz macro cells; • MEC; • sidelink for local team collaboration	• LEO coverage for offshore/ deserts; • Mobile Satellite Service (MSS) L/S-band for alerts; • GEO multicast for manuals
Drones	• Control 10–20 ms; • DL video 10–50 Mbps; • <10 cm positioning	• 5G New Radio (NR) with integrated UAS Traffic Management (UTM); • slicing for Command & Control (C2) vs payload	• LEO for supplemental C2 and telemetry; • GEO/MEO for payload data offload
Healthcare & Training	• Tele-mentoring ≤50 ms; • surgical simulation ≤20 ms	• Quality of Service (QoS) flows, • privacy compliance (GDPR/HIPAA)	• LEO continuity backup; • GEO multicast Continuing Medical Education (CME) sessions
Telepresence	• Round Trip Time (RTT) <50 ms; • jitter <5 ms; • UL/DL 10–50 Mbps	• IMS/Voice over New Radio (VoNR) with XR media; • Segment Routing v6 (SRv6); • Edge SFUs	• LEO for remote sites; • prefetch & FEC for higher RTT
Entertainment & Infotainment	• DL 50–300 Mbps; • low stutter	• mmWave FR2 in venues; • 5G Broadcast (5G-BC)	• GEO/LEO multicast for XR streaming; • edge cache fill via satellite
Space XR	• Latency-tolerant, • asynchronous DTN	• Edge-ground processing, • asynchronous pipelines	• GEO/MEO/LEO/Deep-space DTN; • scheduled sync windows
APIs & Hubs	• Orchestration and observability	• Network Exposure Function (NEF) and RIC/xApps	• API-mediated TN–NTN bonding and capacity brokering

1.3 SPECTRUM AND ORBITAL CONSIDERATIONS FOR XR SERVICES

Building on the KPI mapping presented in Section 1.2 of this Annex, this section outlines how spectrum selection and orbital assets can be optimally combined to meet the performance requirements of representative XR use cases. The allocation of frequency bands and orbital regimes is directly driven by the dominant KPIs (namely latency, throughput, reliability, and synchronisation), while leveraging the complementary strengths of terrestrial networks (TN) and non-terrestrial networks (NTN).

- **XR Interactive Services (Latency- and Synchronisation-Critical):**

  XR interactive use cases, characterised by stringent motion-to-photon latency (10–20 ms), high reliability, and tight synchronisation constraints, are primarily supported by terrestrial spectrum in sub-6 GHz (FR1) to ensure mobility robustness and seamless handovers. High-capacity bands (FR2/FR3) are leveraged for peak throughput demands associated with high-resolution and volumetric XR content. Multi-access Edge Computing (MEC) plays a central role in meeting latency KPIs by enabling local processing and rendering. NTN, particularly LEO systems, can complement TN by providing service continuity and extended coverage, with support for buffered or predictive interaction models where direct real-time constraints cannot be fully met.

- **XR Media Distribution and Content Updates (Throughput-Driven):**

  Use cases dominated by high data volumes but relaxed latency constraints—such as XR media streaming, asset distribution, and application updates—benefit from high-capacity spectrum (Ku/Ka bands) and GEO-based multicast/broadcast capabilities. These enable efficient delivery and pre-positioning of large content volumes into edge caches, reducing real-time network load. LEO constellations provide additional support where moderate interactivity or lower latency access to content is required. In this context, NTN plays a key role in optimising network efficiency and scalability, while TN ensures local delivery and user access.

- **Control, Telemetry, and Alerting (Reliability-Critical):**

  XR-related control and telemetry functions, which prioritise ultra-high reliability and availability over throughput, are best supported by MSS spectrum in L- and S-band. These bands offer superior propagation characteristics and resilience, ensuring robust connectivity in degraded or remote environments. NTN provides a highly reliable fallback and primary communication layer for mission-critical signalling, while TN integration enables seamless end-to-end service management.

- **Latency and Orbit Mapping Across XR Use Cases:**

  The achievable latency associated with different orbital regimes directly maps to the KPI requirements identified in Section 1.2:

  - LEO (~30–50 ms RTT): Suitable for semi-interactive XR use cases and as a complementary layer for interactive services with buffering, prediction, or edge-assisted optimisation.
  - MEO (~120–150 ms RTT): Applicable to buffered, asynchronous, or delay-tolerant XR applications.
  - GEO (~500–600 ms RTT): Best suited for non-real-time services, including bulk content delivery, synchronisation, and multicast/broadcast distribution.

To maintain quality of experience (QoE) across varying latency conditions, advanced techniques such as adaptive buffering, forward error correction (FEC), edge caching, and delay-tolerant networking (DTN) should be systematically applied. These mechanisms enable alignment between network capabilities and XR application requirements, ensuring consistent service delivery across integrated TN/NTN environments.

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